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Use of MERL Microcosms to Study the Fates and Effects of Marine Pollutants

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16. ABSTRACT

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Results from operations through two annual cycles demonstrate that in both chemical and biological composition and chemical and biological processes and annual cycling the systems behaved in ways remarkably similar to comparable regions in Narragansett Bay. Concentrations and fluxes of nutrients and trace metals followed closely those of adjacent Narragansett Bay. Phytoplankton, zooplankton and benthic animals were similar to the Bay in species composition. Biomass estimates were low but generally within bay ranges.

The similarity in chemical cycles between microcosms and the coastal ecosystem suggests that many pollutant substances should behave in the microcosms as they do in the field. Examples of some experiments with hydrocarbons and trace metals are presented

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USE OF MERL MICROCOSMS TO STUDY THE FATES AND EFFECTS OF MARINE POLLUTANTS

by

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Abstract

Informed regulation of the discharge of chemical pollutants into the oceans requires knowledge of the fates and effects of such substances in the regions of concern. In order to provide a capability for realistic controlled experiments, microcosms of a plankton-based coastal marine ecosystem with a benthic component have been set up in 12 tanks outdoors, each with a 5-m deep water column, 13 tons of water and one ton of sediment. The tanks are mixed to achieve proper turbulence, and illuminated with natural sunlight. The behavior of these systems was compared to that of adjacent Narragansett Bay, the source of water and sediments. Experiments have been carried out with hydrocarbons, various tracers, and the scaling of physical parameters.

Results from operations through two annual cycles demonstrate that in both chemical and biological composition and chemical and biological processes and annual cycling the systems behaved in ways remarkably similar to comparable regions in Narragansett Bay. Concentrations and fluxes of nutrients and trace metals followed closely those of adjacent Narragansett Bay. Phytoplankton, zooplankton and benthic animals were similar to the Bay in species composition. Biomass estimates were low but generally within bay ranges.

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Introduction

As man increases in numbers, in technological development, and in the extent to which he exploits the coastal zones of the world, the need for informed management of coastal marine ecosystems becomes increasingly evident. One kind of information needed for this management relates to the biogeochemical behavior and the biological effects of the many substances that we transport and discharge. We need to know what happens when we increase the rates of mobilization and transport of natural substances (e.g., phosphorus, mercury, lead and hydrocarbons derived from crude oil) significantly above the natural geochemical rates and channel this transport into restricted areas, and we need to know what happens when man-made substances (e.g., Kepone, DDT, PCBs, Mirex, plutonium) enter the environment, also often concentrated in restricted areas.

In general, we know too little about the effects of many of these substances on living organisms and too little about what happens to such materials when they enter natural environments. The latter information is crucial. The ultimate impact of any substance entering the environment depends on what happens to it, and with most substances our current knowledge is not adequate for us to predict their pathways and fluxes through the various compartments of natural systems, the rates of destruction, the rates of entrapment in soil and sediment, and the rates of return from such relatively inactive reservoirs back into active participation in food chains.

Studies of lethal and more subtly harmful effects of numerous materials on various test organisms have provided essential information and understanding of biological effects. The number of species that can be tested is limited, however, and they cannot all be tested under all conditions of their normal life cycles. On the other hand, observations in nature, including studies of natural geochemical cycles and various pollution events, suffer from the lack of controlled and replicated experiments. It is especially difficult to provide quantitative information on the geochemical cycles of natural or man-made materials in coastal waters, because of the spatial heterogeneity, complex mixing regimes and rapid temporal transients characteristic of such areas.

These limitations led us to believe that significant advances in knowledge would accrue if it were possible to devise realistic analogues of coastal marine ecosystems that could be used for controlled experimental studies. While there are important differences between laboratory or field microcosms and natural ecosystems, including problems of scale, mixing, large animal exclusion, lack of spatial heterogeneity, etc., the living model or microcosm approach represents a higher level of organization than species cultures and can include more of the many complex activities found in nature (Pilson and Nixon 1980). There are at present no accepted criteria by which it is possible to know whether a microcosm behaves in a

way similar to "nature." In general, we believe that the enclosed systems will be useful experimental tools if they maintain approximately the same rates of chemical transformations and fluxes (total metabolism, uptake and release of nutrients and other trace constituents by plankton and sediments) as the reference natural system, if they maintain similar chemical composition, species diversity and species composition so that the major biological activities are carried on in similar ways, and if their statistical behavior is similar to that of the natural systems. Where they differ, the differences, if sufficiently well characterized, can be taken into account.

The Facility

Twelve microcosm tanks were constructed of FDA-approved fiberglass-reinforced polyester selected for its inertness and nontoxicity. The tanks were arranged outdoors along a platform extending from the laboratory building. Each tank (Fig. 1) contains sediment and a 5-m water column. The sediment container is a shallow fiberglass cylinder, loaded with a sediment layer about 30 cm deep from a region north of Conanicut Island in Narragansett Bay (Fig. 2). The sediment contains a soft-bottom community of animals typical of a large area of the bay, and is characterized as containing Mediomastus ambiseta, a polychaete worm, and Nucula annulata, a small bivalve. Planktonic communities were introduced when the tanks were simultaneously filled with water from the adjacent bay, using diaphragm pumps shown to be non-destructive to zooplankton. The tanks are mixed by a plunger that moves vertically on a cycle (2 hours on and 4 hours off) and provides an intermittent input of turbulent energy (Nixon et al. 1980). The tanks are exposed to sunlight. Water temperatures in the insulated tanks are within 2 ^{o}C of ambient temperatures in Narragansett Bay. At seasons of extreme temperatures, heat exchangers are placed in the tanks to prevent freezing or overheating.

During normal operations, water from Narragansett Bay at the Graduate School of Oceanography (GSO) dock is pumped from a depth of about 2 m below the surface to a header tank, and allowed to flow by gravity through a series of flow control devices into each tank at a rate sufficient to replace the water in 27 days. The flow is pulsed (10 liters per minute for 12 minutes each 6 hours) and between flow periods the pipes drain, preventing fouling problems. The tank walls are cleaned at regular intervals to reduce the fouling community and maintain dominance by the plankton. Further details are given in Pilson (1979) and Pilson et al. (1977, 1979, 1980).

Operations

The first experiments began in August 1976 and ran through September 1977. The tanks were cleaned and refilled in October 1977 and ran through to July 1979. Three tanks were used as controls, both for comparison with experiments in the other tanks and for comparison with Narragansett Bay. Measurements on the systems included both chemical and biological properties (Table 1).

Experiments with hydrocarbons were carried out in three tanks. In the first experiment, a water-accommodated fraction of No. 2 fuel oil was added in one dose to each of three tanks to bring the concentration to about 190 μg ℓ^{-1}. The loss rate of oil and movement into various compartments was monitored over time using gas chromatographic techniques (Gearing et al. 1979). The second oil experiment consisted of a series of twice weekly additions designed to average concentration of the water-accommodated fraction of No. 2 fuel oil at a concentration of about 180 μg ℓ^{-1} from February through July 1977. The third experiment was a repeat of the second, except that the mean concentration was lowered to a value of 91 μg ℓ^{-1} and it ran from March into July 1978. In a fourth experiment, C-14 labelled benzanthracene was added to one tank. The distribution of the benzanthracene and its metabolic products was followed in various components of the system for about 200 days.

Results: Comparison with Narragansett Bay.

We thought it important to compare events occurring in the tanks with those in adjacent Narragansett Bay, even though the bay is a complex region subject to a variety of influences (such as water transport) not modeled in the tanks. Most comparisons have been with stations in the lower west passage of the bay. The comparison has also produced new information on events in the bay.

The annual cycle of nutrients in Narragansett Bay (Fig. 3) is characterized by very low values in the springtime and increasing concentrations through the summer until the early winter. A quantitative explanation of these cycles has not yet been formulated, indicating that we do not have a sufficiently quantitative knowledge of the biogeochemical behavior of these substances in this region. Nor do we understand the reasons for the evident differences from year to year. It is clear, however, that in Narragansett Bay inputs from rivers and sewage, fluxes out of the sediments, uptake by plankton and transport in particulate form to the sediments, and wash-out to offshore, are all important pathways (Kremer and Nixon 1978; Nixon et al. submitted; Pilson et al. 1980).

The MERL tanks have been run through two annual cycles, during which the nutrient concentrations in the tanks followed those in the bay to a remarkable extent. Fig. 4 shows the degree to which individual tanks tracked each other. Figs. 5 and 6 show a comparison of the behavior of the three control tanks compared to that of the bay, for the years 1976-1977 and 1978. Calculation of the exchange and observation of the timing of various events shows that the tanks were not passively following the bay input water but instead were behaving independently but in a similar fashion to the bay. During one 7-month period in 1977 three tanks ("Batch") were not provided with input water; nevertheless during that time the nutrient concentrations were also similar to those in the bay and in the three control tanks.

Trace metals

Observations on dissolved and particulate trace metals were carried out during 1978. Included were measurements of dissolved manganese, copper, cadmium, lead, iron and of particulate manganese, copper, cadmium, lead, iron and aluminum. The concentrations of these trace metals in the tanks were typical of those found in Narragansett Bay, and their seasonal changes were similar (Fig. 7). The rapid increase in manganese during the early spring in both the tanks and the bay is suggestive of similar mechanisms in operation in both systems. The magnitude and timing of the increase in the tanks is such that it cannot have come from the bay via the input water. The benthic flux of manganese measured in the tanks was sufficient to supply the increase. There is a rapid manganese cycle in the tanks, because the benthic fluxes measured during the summer and fall were sufficient to supply each day between 10% and 50% of the standing crop in the water column.

Phytoplankton

The timing and intensity of phytoplankton blooms in Narragansett Bay vary considerably from year to year (Fig. 8; cf. also Pratt 1965, Smayda 1973, 1976). Characteristic features are blooms during the periods from December to April and from June through August. Similar behavior occurred in the MERL tanks (Fig. 8). The general abundance and species composition of the phytoplankton was compared to that in the bay (Pilson et al. 1979 and Vargo in preparation). During August 1976 to September 1977 the mean chlorophyll concentration, a measure of total phytoplankton, in the three control tanks was 69% the bay values, and during the interval from 14 February to 12 September 1978 it was 72%. Throughout most but not all of the period of observation there tended to be somewhat more species in the bay samples than in the control tanks (Fig. 9), indicating a tendency towards greater species diversity in the bay. Overall, there were noted over 70 species or species categories.

Benthic animals

Results from study of benthic animals were given in Grassle et al. (1978).

Oil experiments: #2 fuel oil

Chemical studies on the oil focused on the extent and rates of oil loss and transport to different reservoirs under a variety of experimental conditions. Additions consisted of an oil water dispersion introduced in sufficient quantity to the three oil tanks to maintain a final concentration which averaged 180 $\mu g/\ell$ in the 1977 experiment and 91 $\mu g/\ell$ in the 1978 experiments. These concentrations were maintained for several months. In addition, a number of single tank experiments were carried out to examine a variety of processes.

In March 1978 a single addition was made to one tank to obtain rate constants for the decrease of hydrocarbons in the water. Fig. 10 shows the

type of information obtained. The total hydrocarbons decreased exponentially at a constant rate with a half-life of 151 hours. The composition of total hydrocarbon in the water changed markedly through time, as components of different molecular structure disappeared at varying rates. Overall rates of disappearance measured in tanks 2,7,9 during 1977 were a function of temperature (Fig. 11). The rates of disappearance of oil were affected by both temperature and the prior acclimation of the tanks to the presence of oil. The combined effects (Table 2) provide estimates of the maximum range of half-lives observed, which varied by as much as a factor of nearly 50 depending on conditions and type of compound.

Hydrocarbons disappeared from the water by three routes: incorporation into sediments, microbial degradation, and loss to atmosphere. Fig. 12 shows the increasing concentration of hydrocarbon in the sediments during the 1977 experiment. Concentrations continually increased and an estimated 9% of the oil added to the tanks appeared in the sediment.

Oil experiment: Benzanthracene

About 2 mg of benzanthracene, labeled at the 12 position with C-14, was added to one tank along with a single addition of number 2 fuel oil in water suspension as a carrier. The distribution of the benzanthracene and its metabolic products was followed in various components of the system for about 200 days. The benzanthracene immediately distributed itself in the water column among soluble, total particulate, phytoplankton and zooplankton phases (Fig. 13), some entered the sediment, and some was metabolized completely to CO_2. After about 20 days less than 1% of the benzanthracene was present in the water column. About 6% had washed out of the tank, 14% had been metabolized to CO_2 and 80% was in the sediment (mass balance = 100%). During the seven month period of observation both benzanthracene and various metabolic products gradually moved further down in the sediments and were also slowly metabolized. Polar metabolites were distributed deeper into the sediment than the parent benzanthracene. This experiment provides the most detailed picture yet available on the behavior of a single hydrocarbon substance in any coastal marine ecosystem.

Inorganic tracers

Several experiments have been carried out with about 20 labeled inorganic tracers (Adler et al. 1980; Santschi et al. in preparation; Santschi et al. 1979a, b). These have shown that it is possible to follow in some detail the behavior of inorganic elements in these enclosed ecosystems. By comparison of the flux rates into and out of the sediments (for example) of a natural radioactive element such as thorium it is possible to calibrate the behavior of tracers in the tanks against that in the adjacent coastal ecosystem. Present evidence is that tracers in the enclosed ecosystems behave in a similar manner to that in Narragansett Bay.

Discussion and Conclusions

The remarkable agreement between the nutrient and some trace metal cycles in the tanks and the bay has led to an appreciation that the sediments in the tanks and presumably in the bay must influence the behavior of the whole system in ways that are more dominating than previously thought. It appears that the complex of activities (such as uptake and release of nutrients and other substances by sediments and biota both in the water column and sediments) in these tanks results in whole system behavior quite similar to the bay. An interesting question, yet unexplored, is what would happen if sediments from some quite different location were used to provide the initial conditions.

The species composition of phytoplankton, zooplankton, and benthos were generally similar to those in the bay, with no sustained abnormalities of apparent consequence. Species richness was in general somewhat less in the tanks than in the bay, a finding that was expected. The average biomass supported per unit area has been somewhat less than in the bay. The rates of chemical transformations and fluxes (production, releases from the sediments, respiration), were in general somewhat less than such estimates as we have for some regions of the bay. Most concentrations and fluxes measured were within a factor of two of bay values, which is often within the range of uncertainty of these measurements.

The data for manganese and other trace metals show that the average concentrations were maintained nearly the same as in th bay, presumably by a natural balancing of rates of uptake and release. These data, together with those for the nutrients, provide considerable reassurance that observations on the behavior of various geochemical tracers and pollutant substances in the tanks will provide quantitative information on their behavior and fates in coastal marine ecosystems of the type modeled here.

Detailed observations on the behavior of oil in the microcosms have provided information on the behavior of numerous components under conditions closer to the field situation than has hitherto been experimentally possible. The relationships observed correspond with results of laboratory investigations and theoretical predictions, and also with field observations from accidental discharges. The experimental control of the MERL tanks makes it possible to collect large amounts of detailed information and to provide a quantitative assessment of rates of various processes that are otherwise unobtainable or more weakly founded.

The relatively "natural" behavior of the biological components of these systems in the control tanks (insofar as available measurements are pertinent) suggests that abundant opportunity exists in these microcosms to make observations on numerous subjects of general biological interest, such as feeding, growth, competition and species succession in both plankton and benthos.

Important features of chemical activities in coastal marine ecosystems are the influence of air-water and sediment-water exchange processes. The use of tracers to make quantitative estimates of these processes and of total transport into and out of various reservoirs provides a set of powerful tools that can be used to gain an understanding of the biogeochemical behavior of numerous substances.

These microcosms can be used to provide information on the effects of substances on coastal marine ecosystems and on the processes affecting pathways, rates, possible returns to the food chain and to man, and ultimate sinks, for pollutants and other substances.

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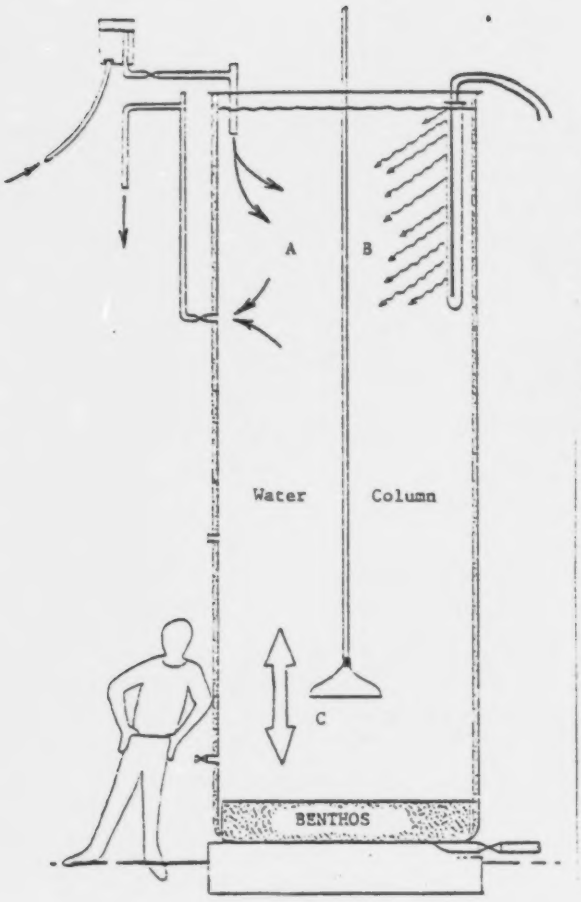
Table 1. Partial list of measurements made in the MERL microcosms and Narragansett Bay, and their approximate frequency. Water column measurements in the bay were made at the GSO dock except for production, which was measured in various ways. Benthic measurements in the bay were made at the benthic station north of Conanicut Island (Fig. 2).

Measurement	Frequency
Dissolved trace metals (Mn, Fe, Cu, Pb, Cd)	weekly
Particulate trace metals (Mn, Fe, Cu, Pb, Cd, Al)	weekly
PO_4^-, NH_3, $NO_3 + NO_2$, $Si(OH)_4$	weekly
Chlorophyll *a*	weekly
Phytoplankton species counts	weekly
Bacteria, planktonic	weekly
Production by C-14	bi-weekly
Light profiles	bi-weekly
Zooplankton biomass and species counts	weekly
Chemical fluxes from sediment	monthly
Interstitial water chemistry	monthly
Macrobenthos biomass and species counts	monthly
Meiobenthos biomass and species counts	monthly

Table 2. Loss rates of various components of Number 2 fuel oil, added to a final total hydrocarbon concentration of about 148 µg/ℓ in each case to one tank in March and one in July, 1978. Temperature about 2°C in March and 20° in July. Tank in March had no prior exposure to oil, tank in July was acclimated to oil at an average concentration of 91 µg/ℓ over the previous four months.

	Half-life, hours	
	March	July
Total resolved saturated hydrocarbons	151	22.6
Total resolved aromatic hydrocarbons	928	29.2
Normal C_{17} alkane	138	19.8
Dimethylnaphthalene	855	17.4



Tanks	
Interior diameter	1.83 m
Interior height	5.49 m
Water	
Depth	5.00 m
Area	2.63 m
Volume	13.1 m^3
Mass	13.4 tons
Sediment	
Area	2.52 m^2
Depth	0.30 m
Volume	0.76 m^3
Mass (wet)	1.10 tons
(dry)	0.57 tons

Fig. 1. Cross section of one of the 12 MERL microcosm tanks, showing the route of water flow, the mixer, sediment container and heat exchanger. The tanks are constructed of FDA-approved fiberglass reinforced polyester resin and have white interior walls. A. Seawater is fed simultaneously into each tank in a pulsed flow manner: 10 ℓ min^{-1} for one 12-minute period every six hours (480 ℓ day^{-1} $tank^{-1}$). B. Temperature control is possible with glass heat exchangers which can both heat and cool. C. Mixing is accomplished with the plunger, 50 cm in diameter, which moves through a vertical excursion of 60 cm at a rate of 5 cycles per minute for one two-hour period each six hours.

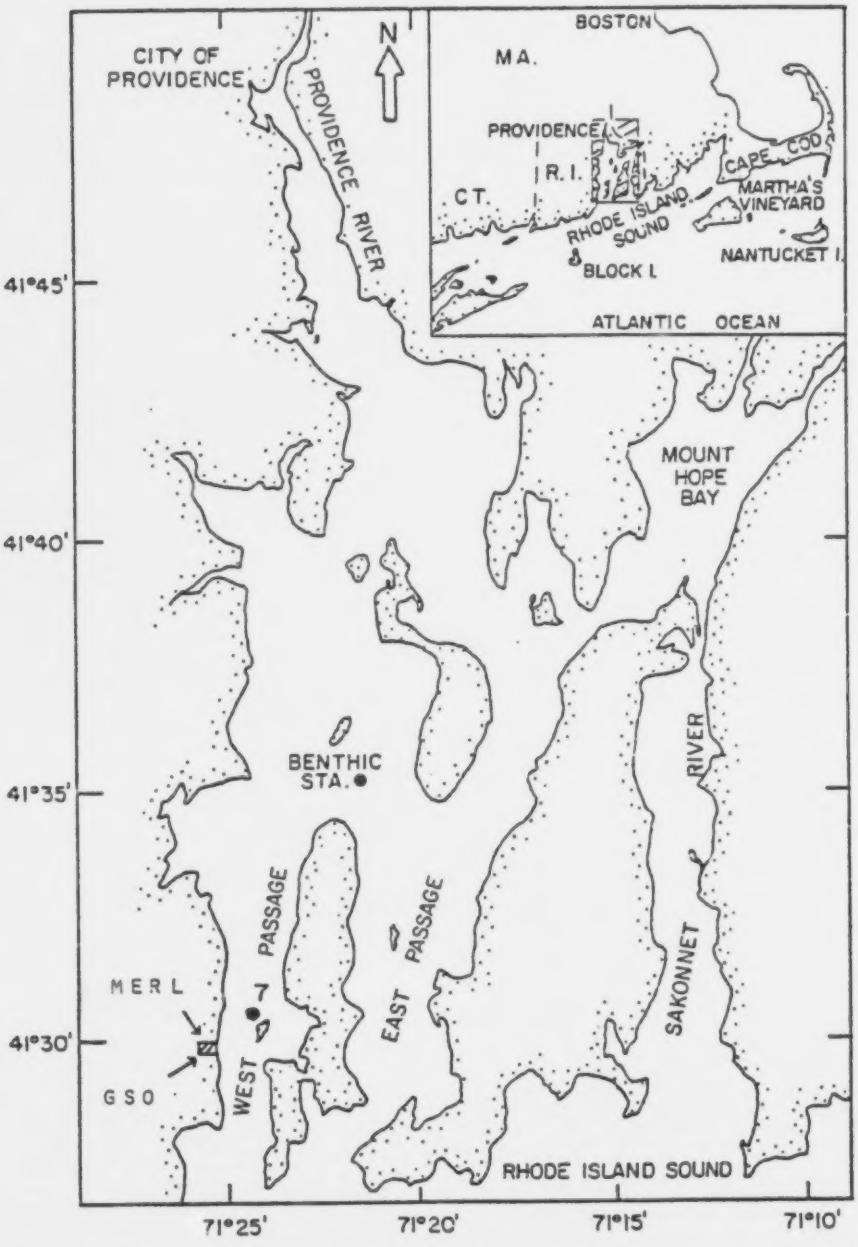


Fig. 2. Map showing locations of the Marine Ecosystems Research Laboratory (MERL) at the Graduate School of Oceanography, University of Rhode Island on the shore of Narragansett Bay and the benthic station from which sediments were taken for use in the microcosm tanks. Data from the numbered station was collected each 2 weeks for a year in 1972-1973, and used for certain comparisons with MERL results.

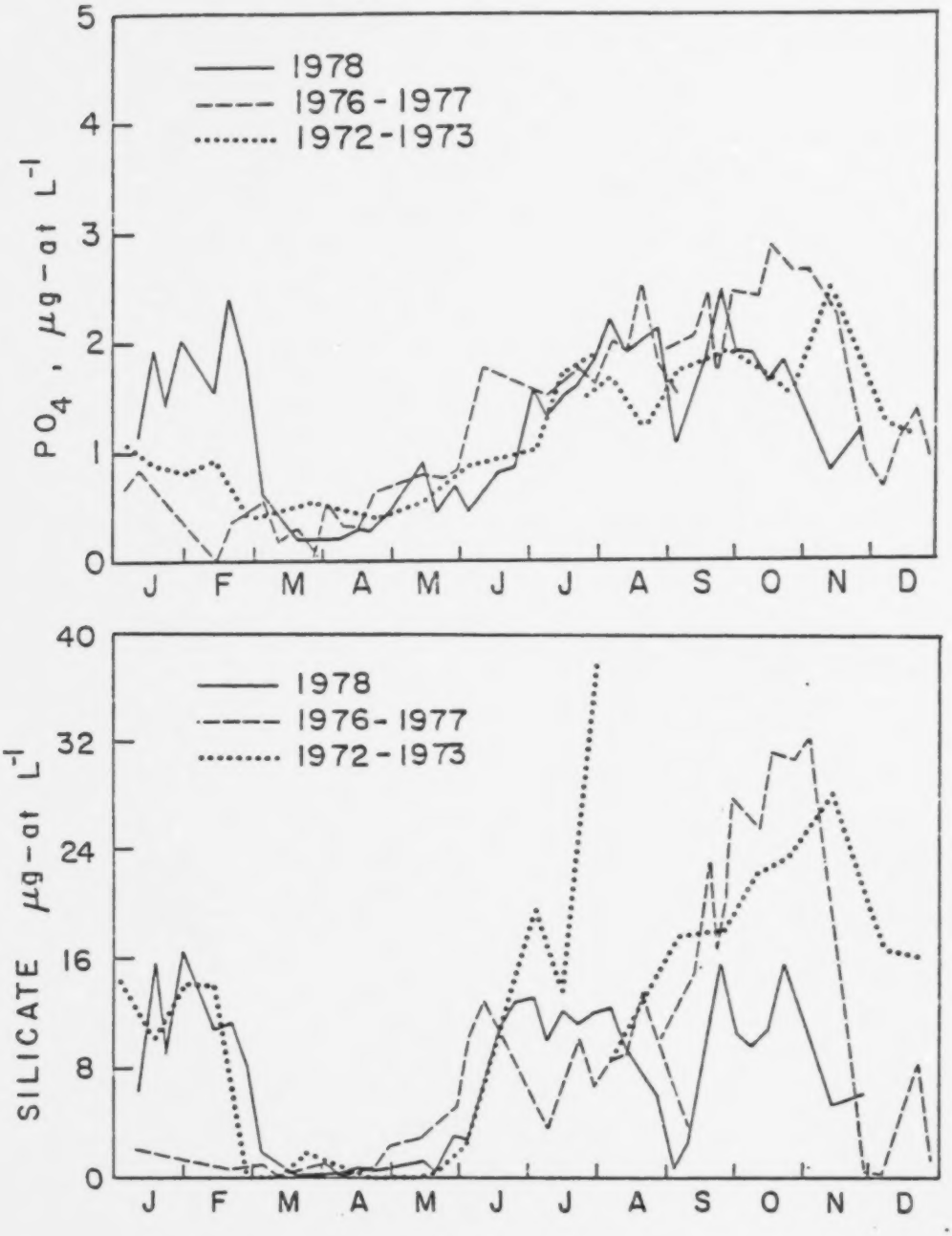


Fig. 3. Comparison of three annual cycles of inorganic phosphate and silicate in Narragansett Bay. Data for 1972-73 collected by Nixon, Kremer and Oviatt (unpublished) at Station 7 (Fig. 2) at approximately two-week intervals from July 1972 through July 1973. Data from August 1976 to September 1977 and for January to December 1978 collected weekly by Vargo at the GSO dock near the MERL facility.

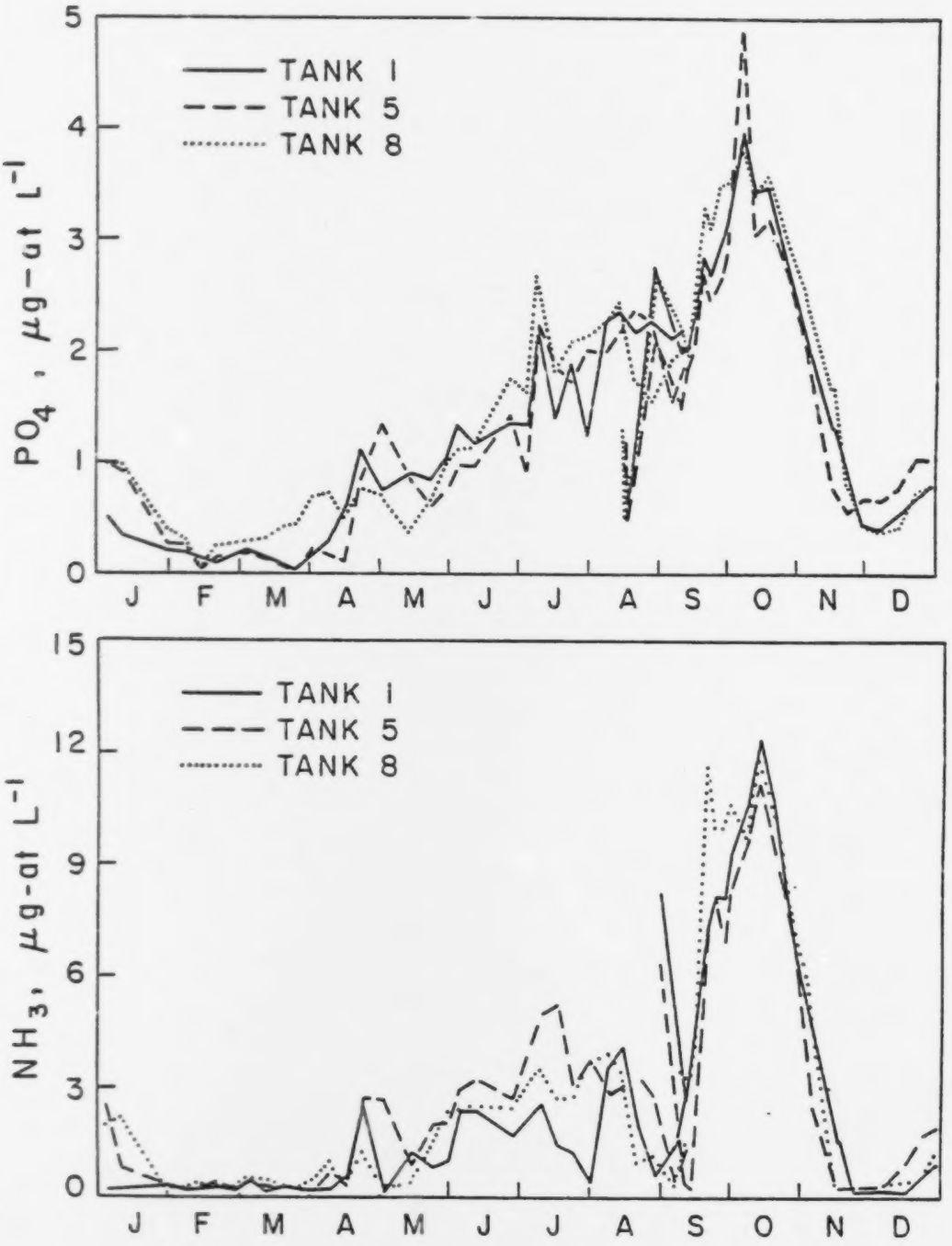


Fig. 4. Phosphate and ammonia concentrations in MERL tanks 1, 5, 8 (control tanks) from August 1976 through September 1977. Measurements made weekly. From Pilson et al. (1980).

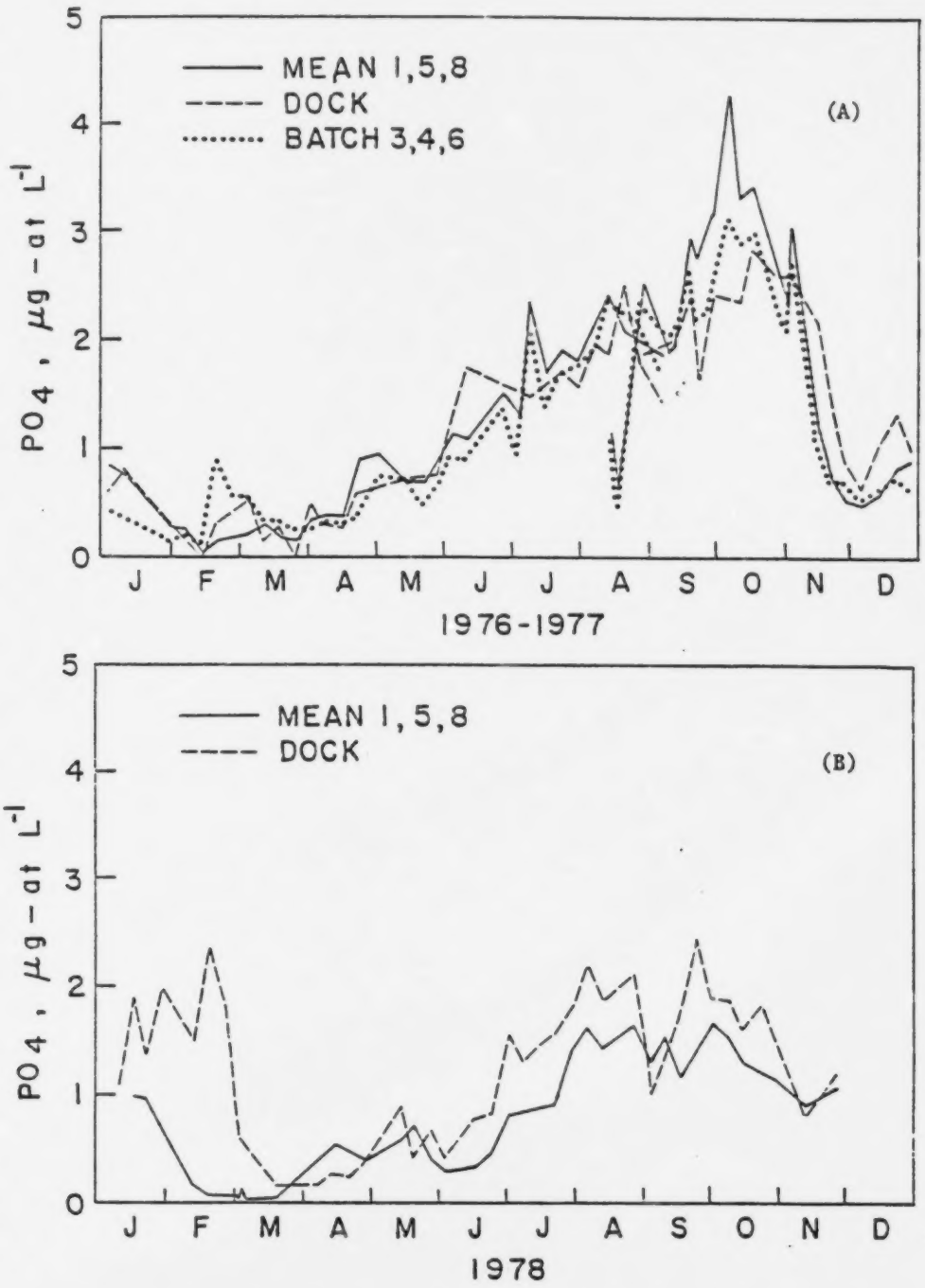


Fig. 5. Concentration of phosphate in tanks and bay during 1976-77 and 1978, measured weekly. (A) Mean values for the three control tanks and for tanks 3,4,6. Tanks 3,4,6 were run in batch mode (no flow-through) from Jan. to Aug. 1977. The rest of the time they were run in the same way as the control tanks. Bay samples from the GSO dock. (B) Comparable data for control tanks and bay for 1978.

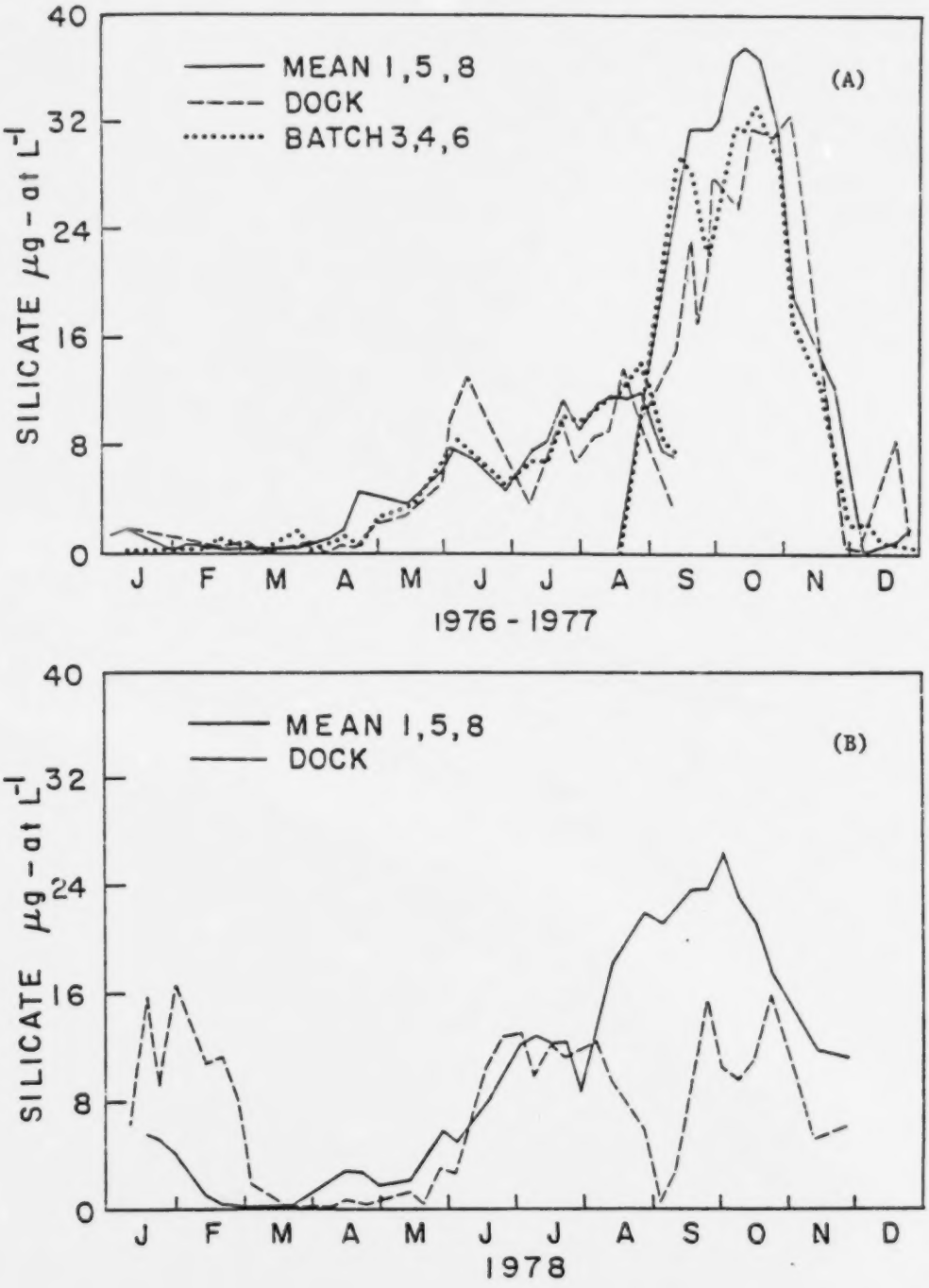


Fig. 6. Concentration of silicate in tanks and bay during 1976-77 and 1978, measured weekly. (A) Mean values for the three control tanks and for tanks 3,4,6. Tanks 3,4,6 were run in batch mode (no flow-through) from Jan. to Aug. 1977. The rest of the time they were run in the same way as the control tanks. Bay samples from the GSO dock. (B) Comparable data for control tanks and bay for 1978.

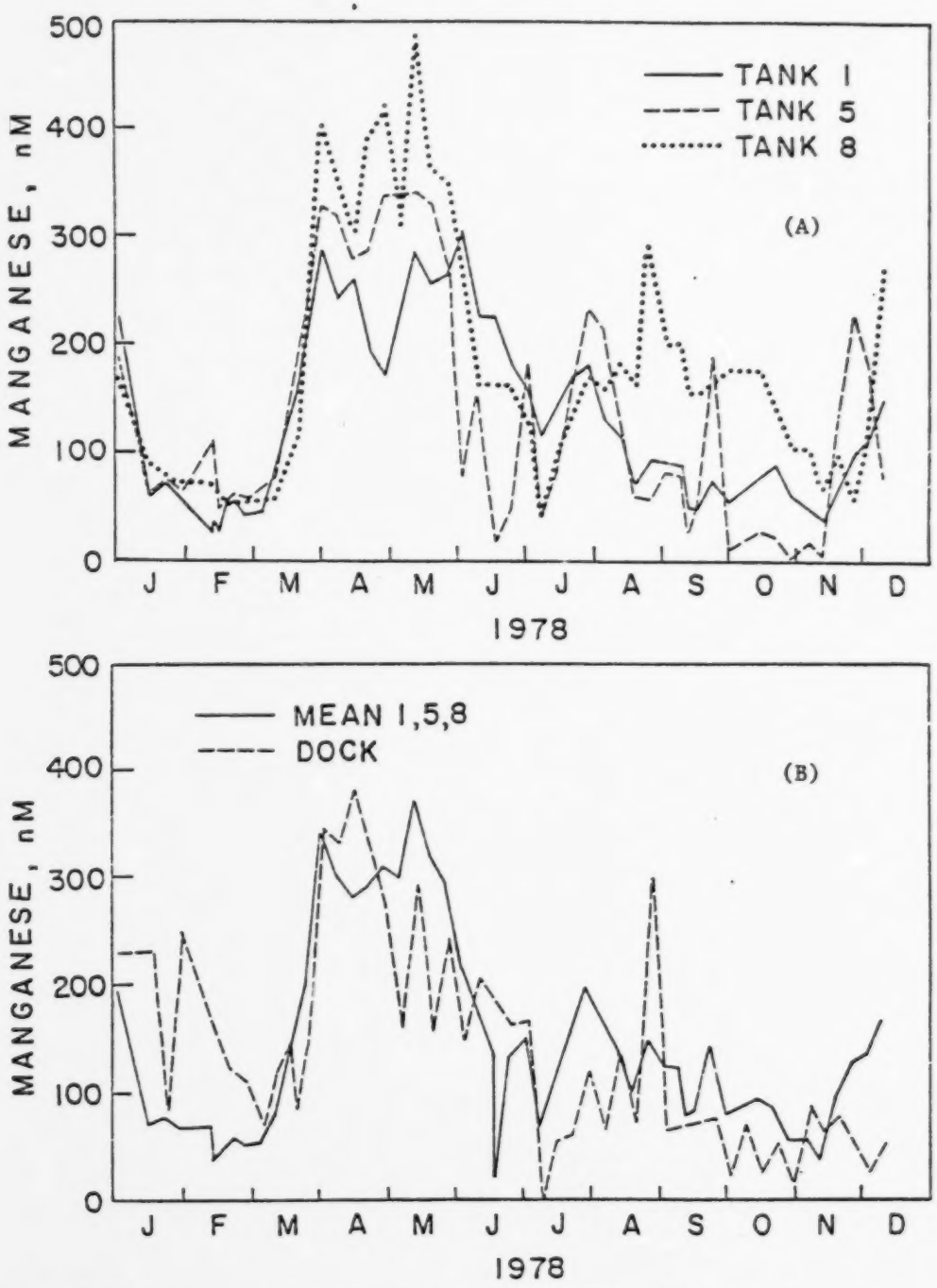


Fig. 7. Concentrations of soluble manganese in MERL tanks 1,5,8 and the bay at the GSO dock, measured weekly in 1978. (A) Three individual tanks. (B) Bay samples compared with the mean of three tanks.

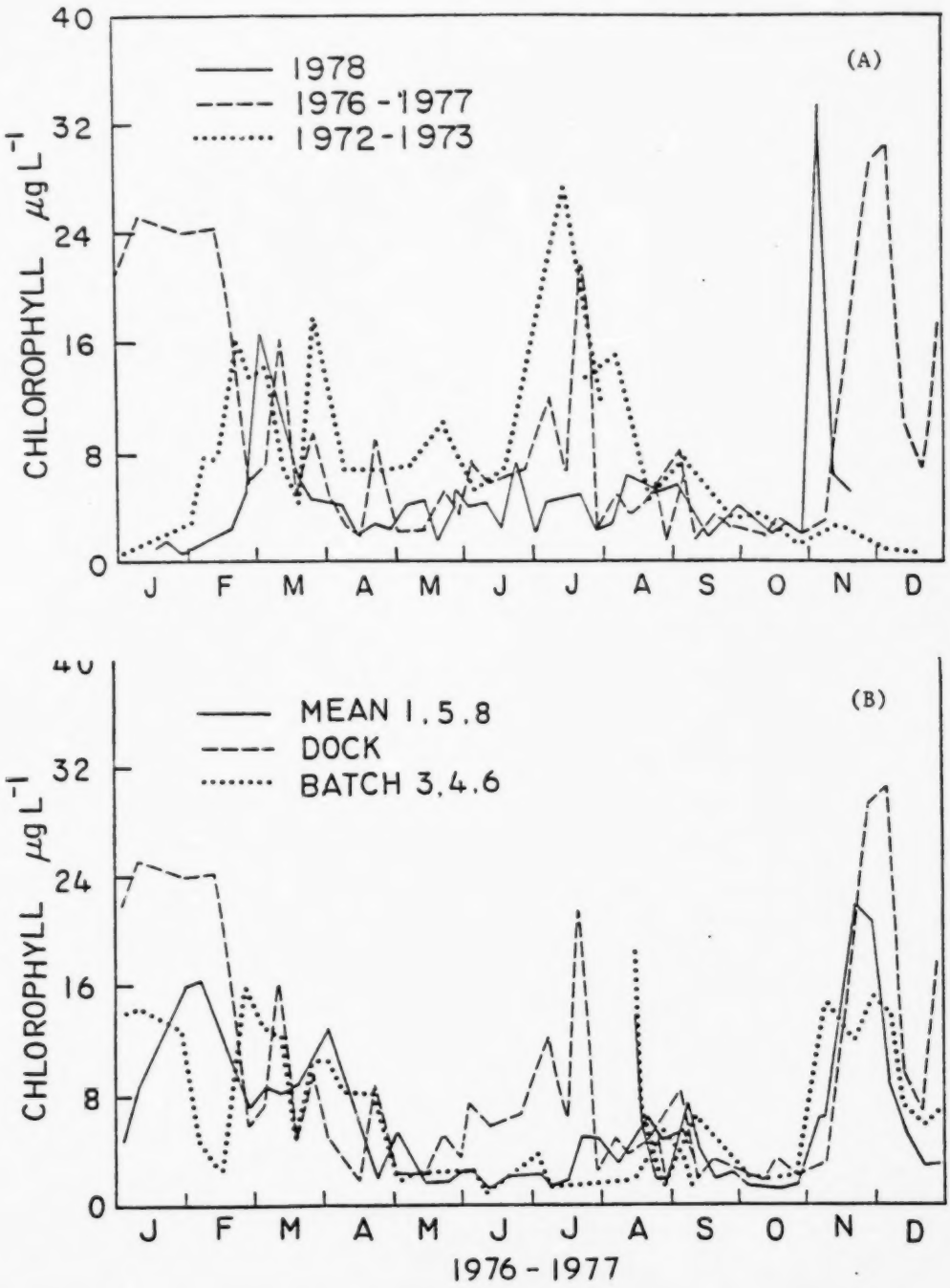


Fig. 8. Abundance of phytoplankton in Narragansett Bay and MERL tanks. A. Chlorophyll a during 1972-73 at Sta. 7 (data from Nixon, Kremer and Oviatt) and in 1976-77 and 1978 at the GSO dock. B. Chlorophyll a in control tanks (mean of 1,5,8) batch tanks (mean of 3,4,6) and GSO dock. Batch tanks were without regular water flow from Jan to Aug, 1978

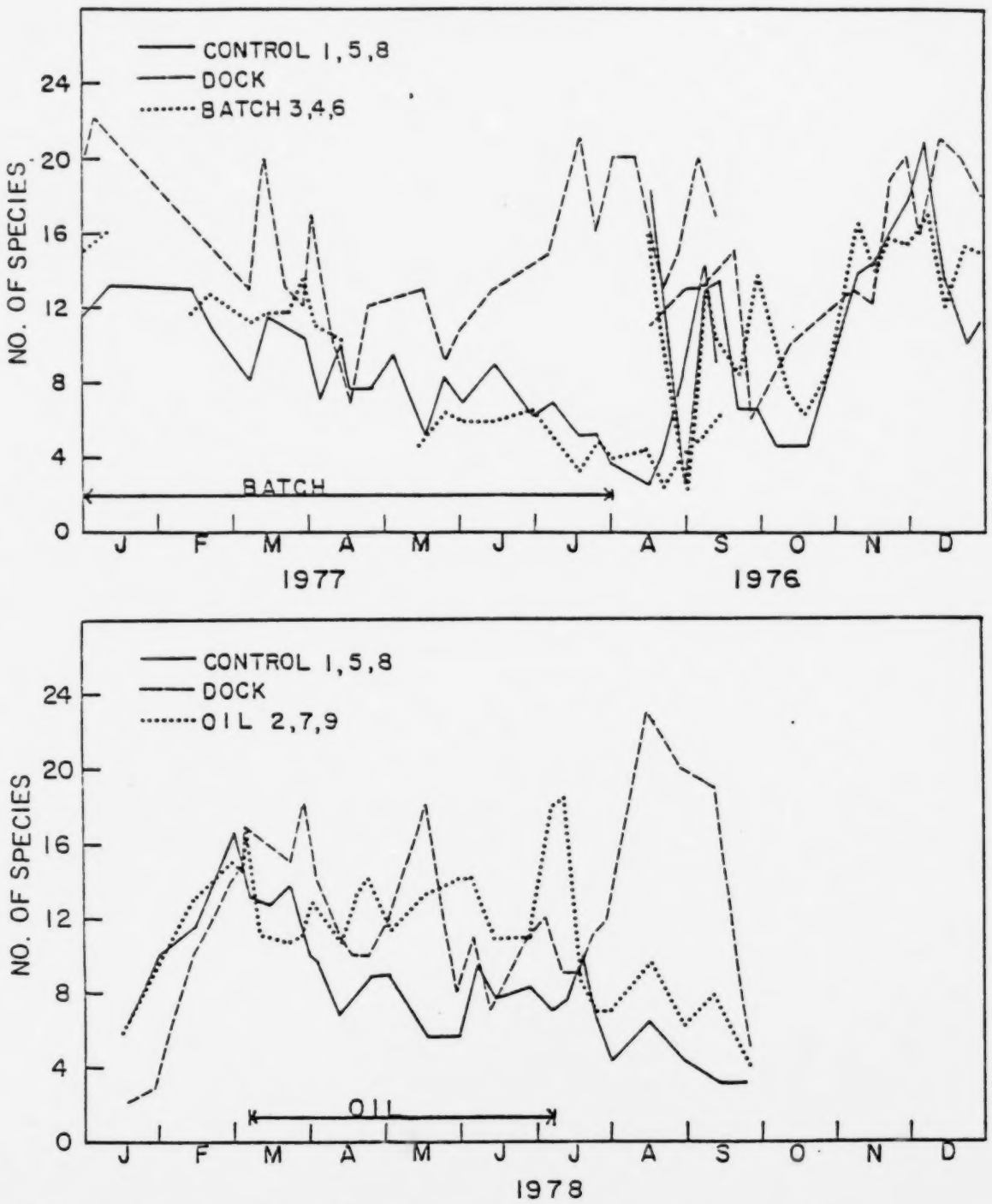


Fig. 9. Number of species of phytoplankton observed in standard counts of samples from the GSO dock and the MERL tanks during 1976 through 1978. The three batch tanks were run with no flow-through for seven months in 1977. In the three oil tanks the average concentration of No. 2 fuel oil was 91 μg ℓ^{-1} during the four month period from early March to early July. Data from Vargo.

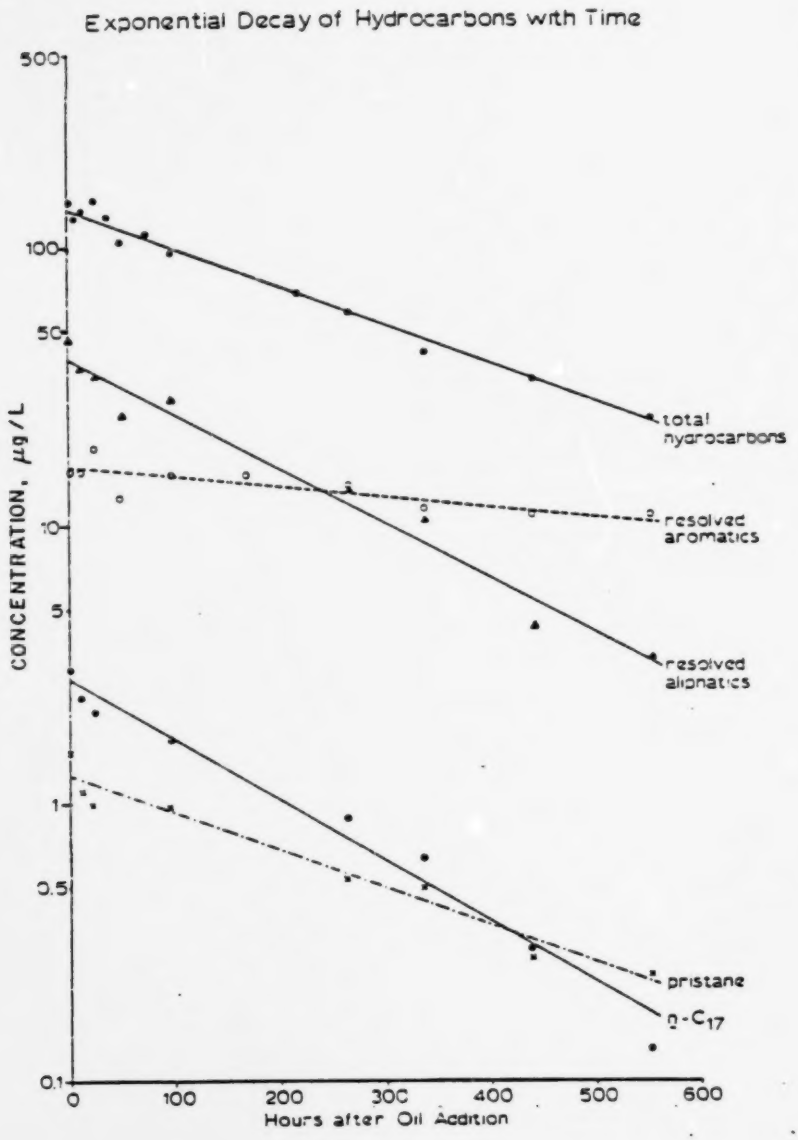


Fig. 10. Exponential decrease in hydrocarbon concentrations with time after a single addition of No. 2 fuel oil to the prototype tank in March, 1978.

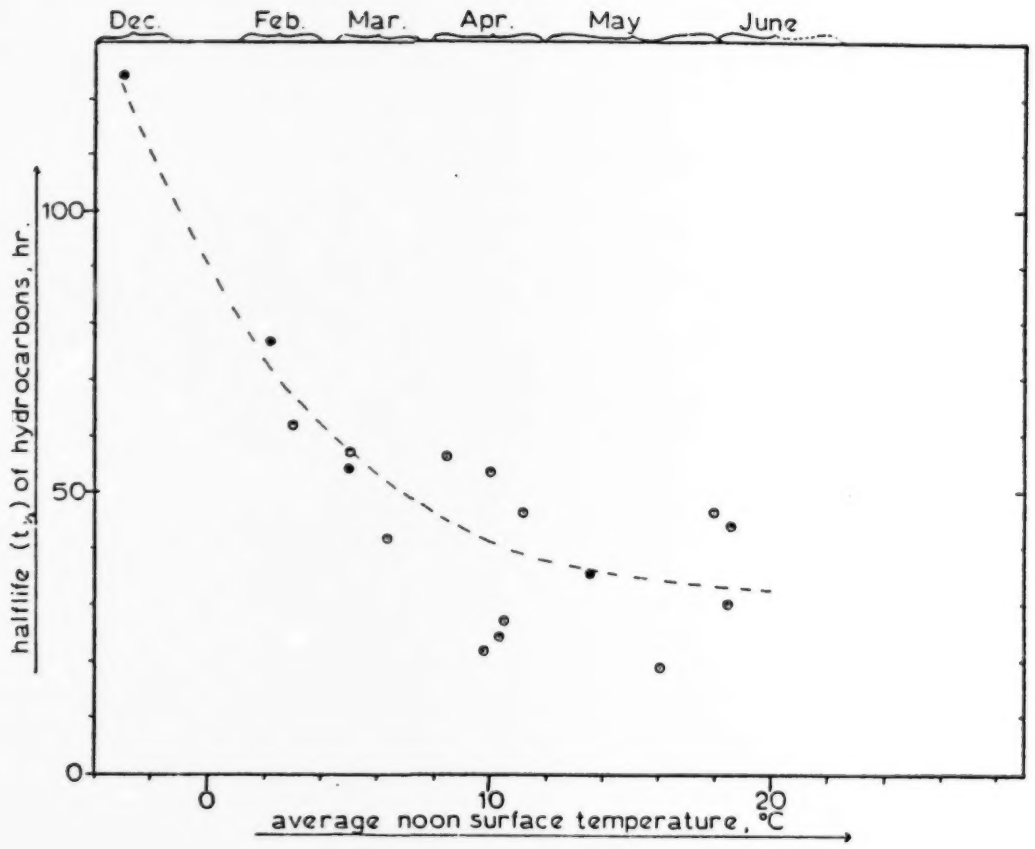


Fig. 11. Half-life of total hydrocarbons in the water column of the MERL tanks, plotted against temperature. Closed circles are from measurements lasting at least a week, providing well defined rates. Open circles are from shorter time series with fewer measurements. Data from Gearing and Gearing.

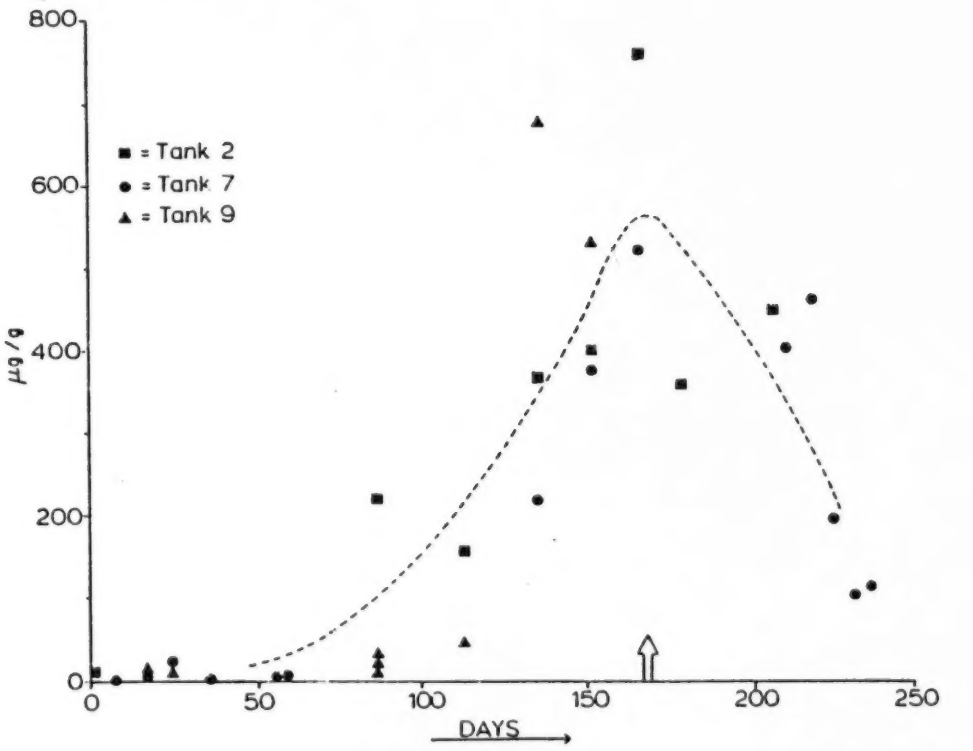


Fig. 12. Concentrations of total hydrocarbons in the top cm of sediments in the MERL oil experiment tanks, showing change with time after the beginning of the chronic oil addition experiment in 1977. The vertical arrow marks the termination of oil additions to the tanks. Adapted from Gearing et al. (1979).

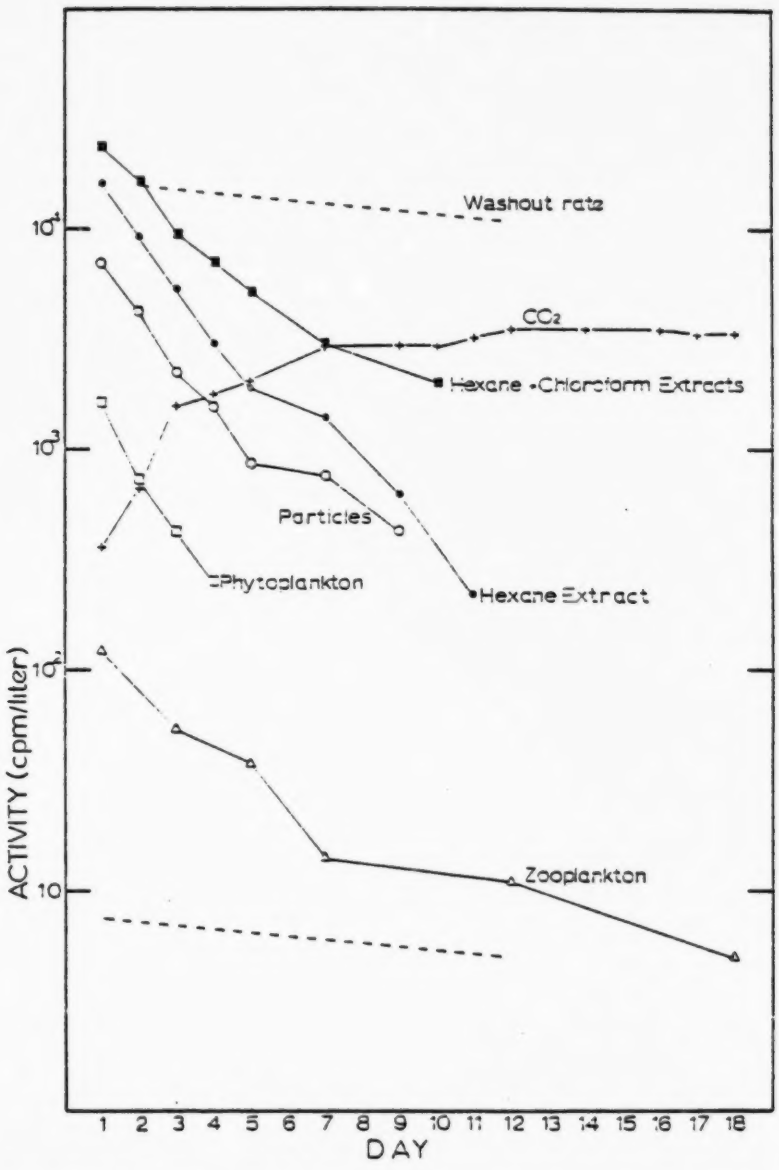


Fig. 13. Distribution of C-14 labeled benzanthracene and metabolites in the water column of a MERL tank after addition of an initial concentration of about 30,000 counts per liter on day 0. The washout rate was calculated from water flows. Terms "hexane extract" and "hexane + chloroform extract" refer to two methods of extracting total water samples. Taken together with sediment data (not shown) the mass balance was close to 100%. Figure from Hinga et al. (in preparation).